Development of a High Energy X-ray Polarimeter for Small Satellites

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Abstract

We are developing a Thomson-scattering-type polarimeter sensitive in the energy range from 10keV to 20keV for a small satellite. The polarimeter consists of three beryllium disks as scatterers and a cylindrical position-sensitive proportional counter as a detector of the scattered X rays. Its performance has been investigated through computer simulations. From these, it was concluded that the polarimeter can obtain a modulation factor of 34%, a detection efficiency of ~10%, and a minimum detectable polarization of about 3.0% for Her X-1 in 2keV bands and a 2×10^5sec observation.

I. INTRODUCTION

Since 1960, much progress has been made in high energy astrophysics due to advancements in detector technology. It has been possible to observe the energy spectrum and time variability of stellar objects in a wide energy range from below 1keV to several hundred GeV. However, for detailed research of radiation mechanisms in stellar objects with strong magnetic fields, such as pulsars, observations of polarization are extremely important, too. Therefore, several polarimeters are being developed for various energy ranges from ~1keV to ~100MeV[1]-[5]. A key energy range, not covered by these instruments is between 10keV and 20keV, and a polarimeter sensitive in this range would compliment the forthcoming SXRP[1] experiment for research of binary pulsars with cyclotron absorption lines. As long integration times are required to obtain scientifically useful polarization data, it is preferable that such a polarimeter be flown aboard a dedicated small satellite and this in turn necessitates an instrument with low weight and power requirements, yet high sensitivity. To address these needs, we are developing a polarimeter sensitive from 10keV to 20keV specifically for small satellites[6].

We utilize the principle that the azimuthal direction of scattered X rays in Thomson scattering depends on the polarization vector of the incident X ray as shown in Eq.1.

$$\frac{d\sigma}{d\Omega} \propto r_e^2[1 - sin^2\theta cos^2\varphi] \qquad (1)$$

where:

r_e = classical electron radius
θ = scattering polar angle
φ = azimuthal angle
for the initial polarization direction

The polarimeter consists of beryllium disks as the scatterer surrounded by a cylindrical multi-wire proportional counter which can detect the azimuthal angle of the scattered X rays by reading out signals from individual anode wires. Because the principle and construction of the polarimeter is simple, the instrument can be developed and built in the 1~2 years' timescale typical of mini-satellite missions.

The performance of a polarimeter is expressed in terms of its Minimum Detectable Polarization(MDP) which is given by Eq.2[7].

$$MDP = \frac{429}{S\eta AM} \sqrt{\frac{S\eta A + B}{T}} \qquad (2)$$

where:

MDP	=	Minimum Detectable Polarization[%]
S	=	Signal Counting Rate[$cm^{-2}s^{-1}$]
B	=	Background Count [s^{-1}]
η	=	Detection Efficiency
A	=	Geometrical Area [cm^2]
M	=	Modulation Factor
T	=	Observation Time [sec]

The modulation factor M is the azimuthal modulation of the scattered X rays for a totally polarized signal and zero background. As is evident from this equation, a high modulation factor, a high detection efficiency, and a large reduction of background are all necessary to achieve a polarimeter with high sensitivity. We designed the polarimeter by optimizing these parameters with computer simulations. In this paper, we will report the basic performance and MDP's obtained for some stellar objects.

II. DETECTOR

In Fig.1, the schematics of our planned Thomson scattering polarimeter are shown. The instrument consists of three beryllium scattering disks and a cylindrical multi-wire proportional counter. For Thomson-scattering-type polarimeters, it is important to scatter incoming X rays as efficiently as possible while avoiding multiple scattering and subsequent photoabsorption in the scatterer. The

most suitable choice of material for the scatterer is beryllium which has low atomic number yet high intrinsic mechanical strength. Even at an optimum thickness of 1cm, though, the probability of scattering is at most 25% at 15keV and so we have introduced three beryllium disks to improve the efficiency. The arrangement of the three disks, their thicknesses, and their radii are optimized by computer simulations using the EGS4[1] code. As a result, the probability of scattering goes up to 38% with the modulation factor still 35% at 15keV, which is similar to the modulation factor(36%) for the case of one disk. Because there are appropriate spaces between each disk, the effect of multiple Compton scattering is suppressed and hence the modulation factor is not compromised. The detection efficiency and the modulation factor are summarized in Tab.1 for arrangements both of three disks and one disk. At the lowest energy, efficiency is low due to photoabsorption in the scatterer. However, the three disk arrangement still provides greater efficiency than one disk.

Table 1
The detection efficiency and the modulation factor at several energies, for 3 disk and 1 disk configurations.

	detection efficiency		modulation factor	
	3 disks	1 disks	3 disks	1 disks
10keV	5.4%	4.5%	33%	37%
15keV	13.1%	7.9%	35%	36%
20keV	12.0%	6.1%	33%	34%

The proportional counter is filled with 2atm of Xe gas and has an inner diameter of 48cm, an outer diameter of 52cm, and a height of 32cm[6]. The inner wall of the proportional counter is made of 1mm thick beryllium and is 93% transparent even for 10keV X rays. The fill gas is 72% absorbing for 15keV X rays. The counter contains 48 anode wires biased at ≈3kV and 48 cathode wires for field shaping at ground potential, wound alternately on a pitch of 1.64cm. The pitch is chosen to minimize the size of regions with weak electric fields, yet keep the number of anode wires as small as possible. A degradation of energy resolution occurs in regions where the reduced field is less than about 150V/cm, due to recombination between electrons and ions[9]. We calculated the two dimensional electric fields of the proportional counter, ignoring the tiny effect of the curvature of the cylinder. The resulting field distribution is shown in Fig.2. The regions where the reduced field is less than 150V/cm are shown as the shaded areas which are about 4% of the total area.

The outer cylinder of the proportional counter is made of 1mm thick stainless steel which is surrounded by passive shielding of tantalum, 0.5mm thick. It is important for passive shields to absorb X rays up to at least 50keV, for which the detector is still efficient. When

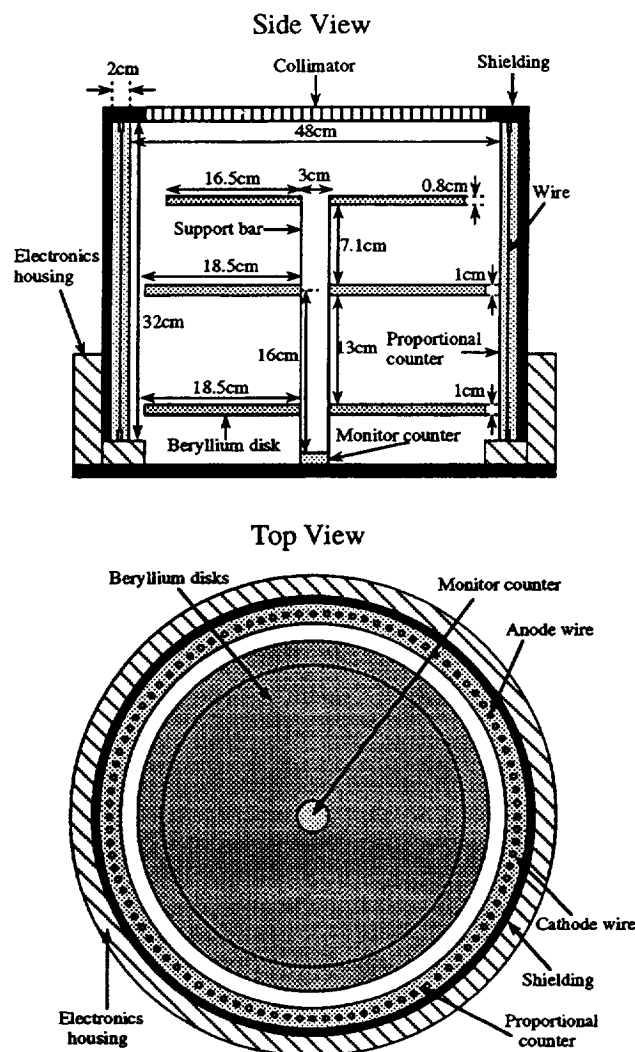[1]Electron Gamma-ray Simulation Version.4[8]

Side View

Top View

Fig. 1 Schematic of the scattering polarimeter. It consists of three beryllium disks as scatterers and a cylindrical multiwire proportional counter filled with 2atm of Xe gas. On the side and the bottom, passive shielding made of 0.5mm thick tantalum are installed. Above the beryllium disks is a field defining collimator made of tantalum.

the X rays are photo-absorbed by the Xe gas, 30keV or 34keV flourescence X rays are generated. In cases where these escape from the proportional counter, the energy deposit from a 50keV photon would show up at 20keV and 16keV, and this could be a serious background component. The passive shields are 98% opaque for 50keV X rays and tantalum does not have flourescence X rays between 10keV and 20keV. The same shield is also installed in the bottom of the polarimeter.

Above the beryllium disks, a tantalum collimator defines the field of view. The collimator consists of 1.3mm circular holes, on a 1.4mm pitch, in a disk 40cm diameter and 2.4cm thick. With this collimator, the field of view is limited to 2.5°(FWHM) and the open area fraction is 78%. During an observation, the polarimeter
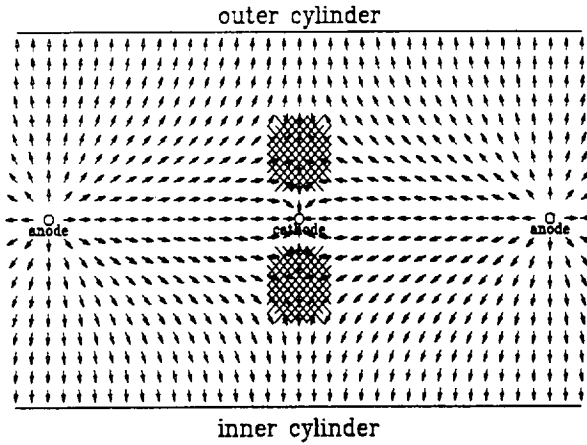
outer cylinder

inner cylinder

Fig. 2 Reduced fields in the proportional counter. In the figure, the directions of the electric fields are shown as arrows. The region where the reduced fields are less than 150V/cm is shown as a shaded area. This area is less than 4% of the total.

is rotated about the line of sight. The rotation technique removes spurious modulations such as would be caused, for example, by an azimuthal non-uniformity of detection efficiency of the proportional counter. The collimator has a uniform circular response designed to minimize additional modulation components for sources off–axis. Finally, a monitor counter is installed which views the observed source directly through a hole in the center of the beryllium disks. It is used to reduce any spurious modulation caused by time variability intrinsic to the source.

An important parameter for sensitivity calculations is an estimate of background. For efficient reduction of charged particle background, we adopt the following two methods. As a charged particle passes through the proportional counter, it ionizes the Xe gas along a track of typical length $\geq$ 2cm. On the other hand, a primary electron emitted by the photoabsorption of X rays in our 10~20keV band only extends ~1mm. The difference will be reflected in the risetime of the signals from the anode wires. So, the charged particle events can be rejected by pulse shape discrimination on the anode signals. Also, because signals from charged particles typically trigger several anodes, it is expected that mutual wire veto will provide additional background suppression. The rejection rate of background of charged particle tracks in the detector is expected to be about 98%. Secondary γ rays could, however, be a serious background component generated when charged particles bombard materials in the space craft. Scaling data obtained from the Ginga satellite mission[10], we estimate this background component to be about 10 counts/sec from 10keV to 20keV, for our polarimeter. Finally, we calculate background by cosmic diffuse X rays using the EGS4 simulation program. The background of the polarimeter is simulated with the spectrum[11] given in Eq.3, which gave a total rate of ~2counts/sec in the energy range

from 10keV to 20keV.

$$\frac{5.6}{E} \times [E/3]^{-0.29} exp(-E/40) cm^{-2} s^{-1} kev^{-1} str^{-1} \quad (3)$$

The characteristics of the polarimeter described above are summarized in Tab.2. The total weight of the instrument, including electronics is around 60kg and this is typical of small satellite payloads.

Table 2
The characteristics of the scattering polarimeter (see text). The estimated background rate is due to cosmic diffuse X rays and secondary γ rays generated by charged particles.

Energy range	10keV~20keV
Geometrical area	975cm^2
Field of view	2.5°(FWHM)
Modulation factor	~34% between 10keV and 20keV
Detection efficiency	5~13% between 10keV and 20keV
Estimated background	~12counts/sec
Total weight	~60kg

III. MINIMUM DETECTABLE POLARIZATION

Our full-up simulation using EGS4 allows us to calculate the MDP's at 99% confidence level for several stellar objects, such as binary pulsars[12]–[14] and a synchrotron nebula[15]. The results are shown in Fig.3 and Tab.3. For the case of the Crab Nebula, which was
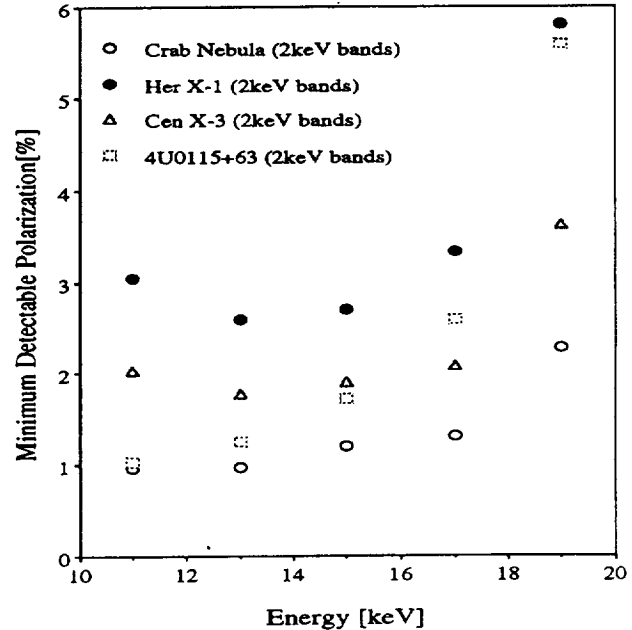

Fig. 3 The MDP's of several stellar objects in 2keV bands for 2×10^5 sec integrations.

measured to be 19.7% polarized at 2.6keV and 5.2keV by Weisskopf et al[17], the same or greater polarization

Table 3
The MDP's for several stellar objects in 10keV bands for a 2×10^5sec integration time. The MDP's of all the objects are less than 1.5%.

	Crab Nebula	Her X-1	Cen X-3	4U0115+63
MDP	0.5%	1.4%	1.1%	0.7%

would be expected in the energy range above 10keV. As the MDP of our polarimeter is less than 2.5% for the Crab Nebula in 2keV bands, for a 2×10^5sec integration, it can easily detect this polarization. The polarization from pulsating X-ray binaries is expected to be quite large, possibly as high as 50%[16]. As the planned polarimeter has an MDP better than 6% in 2keV bands and 1.5% in a 10keV bands for the three examples of X-ray binaries given here, it should also be easily able to detect polarization from these sources as well.

IV. CONCLUSION

Observations of X-ray polarization are necessary to study the features of stellar objects with strong magnetic fields. Nonetheless, polarizations of stellar objects have never been succesfully measured except for the Crab Nebula, so we have designed a Thomson scattering-type polarimeter, sensitive in the energy range between 10keV and 20keV, to address these needs. Its performance has been investigated through computer simulations which show that the polarimeter can obtain a detection efficiency of about 10% and a modulation factor of 34%. It is expected that it can easily detect the polarization from the Crab Nebula, and binary X-ray pulsars such as Her X-1, at 99% confidence levels in 2keV bands for 2×10^5 integrations, if they have a polarization of a few percent or more. It may, in addition, be possible to measure the polarization with pulse phase in these sources, providing additional valuable information. In a broader band, 10keV, it can detect polarizations with MDP's better than 10% for many more targets.

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